

Chapter 16

Bioenergy Systems, Soil Health and Climate Change

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16.1 Introduction

Currently fossil fuels supply most of the world's energy needs, in processes that move carbon from geologic pools to the atmosphere. In 2007, use of fossil fuels released an estimated 28.8 Gt of carbon dioxide equivalent (CO₂-e) into the atmosphere (International Energy Agency 2009). The increasing atmospheric concentration of carbon dioxide (CO₂) and other greenhouse gases (GHGs) influences climate (Solomon et al. 2007), and this process may be accentuated if climate and carbon cycle feedback loops continue to develop (Friedlingstein 2008; Gregory et al. 2009).

It is generally accepted that we need to move to a “low-carbon future” with reduced reliance on fossil fuels for energy. Bioenergy can play a significant role, meeting some of our energy needs while reducing carbon emissions and even sequestering significant amounts of carbon. While there is the potential for bioenergy systems to provide very significant amounts of energy across the world (Bauen et al. 2010), intensifying production systems and changing land use and land management to produce biomass may impact on soil health and soil carbon in particular (Lal et al. 2003). The question of how bioenergy systems should be managed to achieve optimal outcomes is not yet clearly resolved (e.g. Blanco-Canqui 2010; Cowie et al. 2006; Delucchi 2010; Lal et al. 2003). And while bioenergy systems, if thoughtfully designed, can contribute to *mitigating* climate change, we also need to consider some of the issues in *adapting* to climate change to sustain production.

The impacts of bioenergy systems on soil health and climate change are relevant at various scales:

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- At the local scale, where bioenergy systems may influence physical, chemical and biological properties of soils, affecting productivity, soil health and carbon sequestration;
- At the catchment scale where bioenergy systems may affect regional hydrology and water quality, influencing carbon stocks and potentially soil health;
- At a global scale where biomass production may cause competition for land, leading to deforestation and consequential loss of carbon stocks, sometimes in locations distant to biomass production.

Conversely, intensification and expansion of bioenergy could involve revegetation of marginal lands potentially enhancing terrestrial carbon stocks. To manage potential sustainability impacts on these various scales will require the development of robust and clear assessment protocols (van Dam et al. 2010). This is an area of significant and evolving policy and will have significant impacts on bioenergy systems and their development to meet local and global needs.

16.2 Definition of Bioenergy, Soil Health and Climate Change

Bioenergy is a composite word, combining “biomass” and “energy”. Bioenergy is the production of heat, power and liquid fuels (termed biofuels) from biomass. Biomass is plant matter or derived from plant matter, and can be sourced from processing and post-consumer residues, in-field residues from forestry and agriculture, and purpose-grown energy crops. In this chapter, we consider the impacts on soil health of the latter two sources of biomass. Similar to Raison and Khanna (2011), we use the description of “soil health” offered by (Doran and Zeiss 2000) as *the capacity of the soil to function as a vital living system, within ecosystem and land use boundaries to sustain plant and animal productivity, maintain or enhance water and air quality and promote plant and animal health*. Furthermore, we include all significant soil physical, chemical and biological properties and processes that affect bioenergy systems and are in turn impacted by utilisation of land for biomass energy production.

The potential for bioenergy to mitigate climate change is a major driver of the recent policy development and industry expansion. Following the Intergovernmental Panel on Climate Change (IPCC) definition, we define climate change as *a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use* (IPCC 2001).

In much of the literature reference is made to the potential for biomass production in marginal or degraded soils (or landscapes). We use the United Nations Environment Programme (UNEP) definition of “land degradation” as *a long-term loss of ecosystem function and services, caused by disturbances from which the*

system cannot recover unaided. Thus degraded land has lower productivity as a result of human actions, sometimes interacting with natural factors (e.g. overgrazing in drought).

“Marginal land” is land on which the value of produce barely exceeds production costs. It could be marginal because it is degraded or there may be other constraints such as soil type or climate. “Marginal” is context related and is subject to current technologies, plant breeds, agronomic practices, market values, etc. Thus, an area may be considered marginal with respect to one land use but not another.

16.3 Policy Drivers Increasing Bioenergy

Bioenergy generally costs significantly more than existing fossil fuel-based energy sources (Duer and Christensen 2010), but it is promoted for various reasons including:

- Energy security;
- Environmental benefits, particularly mitigation of climate change;
- Rural and regional development;
- Human health.

The development of bioenergy is encouraged by policies including renewable energy targets, industry development grants and emissions trading (Capon et al. 2010; Vivid Economics 2010). However, there are concerns about potential impacts of the expansion and intensification of large-scale bioenergy systems including:

- The “food versus fuel” debate – it has been asserted that utilisation of food for fuel [particularly corn (*Zea mays*) for ethanol] has led to rising food prices (Pimentel et al. 2009), but others claim that this impact has been exaggerated (Baffes and Haniotis 2010) or can be avoided by integrating food, feed and biomass production (Dale et al. 2010). Nevertheless, the stronger competition for resources as the human population grows could be a significant challenge for future bioenergy development (Bartle and Abadi 2010; Fischer et al. 2009; Pimentel et al. 2008; Solomon 2010; Tilman et al. 2009).
- The actual net GHG balance of bioenergy systems – some systems may deliver minimal GHG savings, when production-chain emissions and impacts on terrestrial carbon stocks are accounted (Fargione et al. 2008; Halleux et al. 2008; Tyner et al. 2010).
- Indirect land use change (iLUC) – use of agricultural land for biomass production may lead indirectly to deforestation, with implications for soil health and climate change (Delucchi 2010; Fischer et al. 2009; Schlamadinger et al. 2007).
- Local environmental impacts – for example, impacting air quality due to increased emissions in production of energy from biomass crops and biofuel refining; reduced water supply where production of biofuels uses significant water; and soil health (Blanco-Canqui 2010; Lasch et al. 2010; Lattimore et al. 2009).

To secure the confidence of policy makers, on behalf of society, the bioenergy industry needs to demonstrate that production can meet energy needs as well as environmental and social objectives. Sustainability frameworks are being developed to give confidence that bioenergy production will deliver energy security and GHG mitigation while minimising negative impacts such as soil degradation (Fritsche et al. 2010; O'Connell et al. 2009; van Dam et al. 2010). We discuss these frameworks in more detail in Sect. 16.8.

Well-planned bioenergy systems have the potential to provide continuous, large-scale supplies of energy that displace fossil fuels at economically competitive rates without negatively impacting on the environment. Developing such robust systems presents many challenges; in this chapter, we focus on soil health impacts and do not address other environmental impacts or issues such as social impacts, technology development, commercialisation and trade facilitation.

16.3.1 The Role of Bioenergy in Providing Renewable Energy

Bioenergy contributes approximately 10% of the primary energy mix globally, with nearly 9% from woody biomass and the remainder ($\approx 1\%$) from agricultural crops and by-products plus municipal and industrial wastes (Bauen et al. 2010). Biomass uses range from low technology traditional use of firewood for heating and cooking, to co-firing in large-scale power plants (Berndes et al. 2010) and dedicated heat and power generation (Bernotat and Sandberg 2004). In northern European countries and North America, policy development has led to significant biomass use. For example, in Sweden bioenergy contributes $>20\%$ of the national primary energy supply (Alm et al. 2009). By comparison, in Australia, which has abundant supplies of coal and thus low-cost electricity, the contribution of bioenergy is much smaller, comprising 3.6% of the total primary energy in 2007–2008 (ABARE 2010).

The potential for bioenergy to contribute to future national and global energy needs is significant but estimates vary widely. Some consider that bioenergy could sustainably contribute 25–33% of primary energy needs by 2050 replacing fossil fuels in all energy markets (viz. electricity, heat and transport) (Bauen et al. 2010). Much of the uncertainty regarding the capacity to “sustainably” produce feedstock for bioenergy relates to the potential impact of competition for water and land resources, especially as the world population increases. The literature is split between very positive assessments of bioenergy capacity (e.g. Bartle and Abadi 2010; Fischer et al. 2010; Hoogwijk et al. 2009; Wit and Faaij 2010) and those that are negative, predominantly due to concerns over energy or GHG balance (e.g. (Fargione et al. 2008; Pimentel 2009) or conflict with food production (e.g. Pimentel et al. 2009; Schade and Pimentel 2010; Solomon 2010). Studies of likely capacity to produce biomass must, by definition, be hypothetical, based, for example, on assumptions about population growth, technological development and climate change impacts. Importantly these studies determine boundaries of

theoretical potential and highlight considerations in developing large-scale production systems. We discuss many of the specific issues in detail below.

The extent to which bioenergy contributes to future global energy requirements will depend on:

- The biophysical capacity to produce biomass feedstock, process and transport energy carriers (Bauen et al. 2010; Berndes et al. 2010);
- Market development (Hansson and Berndes 2009; Hoogwijk et al. 2009);
- Technological development of feedstock conversion including pre-treatment (Uslu et al. 2008) and biorefinery development (Cherubini 2010);
- Social and environmental objectives and limitations applied through policy (Delucchi 2010; O'Connell et al. 2009).

16.3.2 Bioenergy and Climate Change

The major policy driver for the current promotion of bioenergy is its potential to contribute to climate change mitigation. Bioenergy systems can displace the use of fossil fuel, leaving the fossil fuel “in the ground”, and may sequester carbon (through storage of carbon in the soil or vegetation). The potential benefit from increasing biomass energy (stationary and transport) and avoiding fossil fuel use is significant. The IPCC estimates that by 2030, increased energy generation efficiency and switching to alternative low-carbon sources including bioenergy could reduce emissions by approximately 1.6–2.5 Gt CO₂-e per annum for light transport (Ribeiro et al. 2007), and between 2.0 and 4.2 Gt CO₂-e per annum for stationary energy production (Sims et al. 2007).

To determine the mitigation value of bioenergy, we can use the *displacement factor*:

$$D_f = \frac{\text{Efficiency of bioenergy system}}{\text{Efficiency of displaced fossil fuel system}} \times \frac{\text{CO}_2 \text{ emissions per J fossil fuel}}{\text{CO}_2 \text{ emissions per J biofuel}}, \quad (16.1)$$

where D_f is the “amount of carbon emission from fossil fuels that is avoided when biofuels are used instead” (Schlamadinger and Marland 1996) and is a unitless measure. The efficiency of energy production is often summarised by the concept of the *energy return on investment* (EROI). The EROI is determined by the amount of energy gained from a process compared to how much energy was required to grow (or extract) and transform a new unit of energy carrier (e.g. biomass material) into the useable energy in question. Larger EROI indicates a more efficient production of useable energy from primary sources.

Also important are the production-chain emissions, due to: fossil fuel use, for example, in cultivation, harvest, transport, fertiliser manufacture; non-CO₂ emissions, such as nitrous oxide (N₂O) from applied fertiliser; and change in

biomass and soil carbon. Co-products can also have a significant impact on the GHG balance of some bioenergy systems: biochar, a co-product of pyrolysis, can be used as a soil amendment improving soil health and yielding mitigation benefits [(Cayuela et al. 2010); also see Chap. 15 and Sect. 16.6.4]; residues from ethanol and biodiesel production can be used as animal feeds, saving emissions associated with feed production (Dale et al. 2010). Land use change (LUC), both direct and indirect, can significantly add to the production-chain emissions of bioenergy systems (see Sect. 16.7).

While climate change is a major driver for the industry, mitigation value must be balanced with other objectives. This becomes a challenge for policy development and implementation, as there are often trade-offs: maximising carbon sequestration and biomass production may reduce potential biodiversity benefits, or adversely impact hydrology. However, there are potential “win–win” scenarios where mitigation, conservation and production objectives can be addressed simultaneously, for example, the development of a mallee industry for bioenergy production in Western Australia (Bartle et al. 2007).

To make a significant contribution to climate change mitigation, a huge quantity of biomass will be required (Bauen et al. 2010; Raunekar et al. 2010). For example, it is estimated that for the USA to produce 30% of their domestic transport fuel demand would require the growing and processing of approximately one billion tonnes of biomass per annum (Perlack et al. 2005). The potential impact on GHG emissions of large-scale bioenergy systems will require carefully developed policy to meet multiple objectives and optimise production.

16.4 Land-Based Bioenergy Systems

There is great variation among bioenergy systems with respect to biomass feedstocks, transformation processes and energy services delivered (Fig. 16.1). In future, algae may become a significant source of biomass for biofuel (Florentinus et al. 2008; Wijffels and Barbosa 2010), but as algae-based systems will have limited impacts on soil health, they are not considered further in this chapter. Rather, we focus on the biomass feedstock production, as this is the stage that predominantly influences soil health.

Biomass for energy systems can be sourced from:

- Crops specifically produced for energy purposes [e.g. sugar cane (*Saccharum* spp.), wheat (*Triticum* spp.), sorghum (*Sorghum bicolor*), rapeseed (*Brassica napus*), short rotation woody crops (SRWC)]. Many of these crops already have competing uses.
- Residues that can be classed as:
 - (a) Primary residues, produced during the production of forest products and food crops (e.g. forest thinnings, crop stubble). These resources are generally available in situ and must be collected (i.e., they are a dispersed source of material).

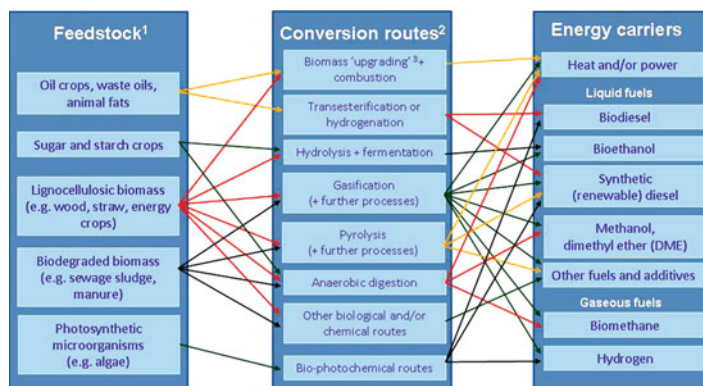


Fig. 16.1 Bioenergy feedstocks can be produced through many different pathways and then converted to meet various energy needs through a multitude of conversion routes (sometimes with multiple processes). The feedstocks will be produced from various primary, secondary and tertiary sources or dedicated energy crops (¹Different parts of each feedstock can be used in other and/or multiple conversion routes; ²Each route may also yield co-products (e.g. bagasse for cogeneration as a co-product of sugar production from sugarcane); ³“Upgrading” includes a densification process such as pelletisation or torrefaction; [adapted from Bauen et al. (2010) with permission]). Only energy related products are considered in this diagram. Other bioproducts (e.g. bioplastics, biochar) are not explicitly incorporated

- (b) Secondary residues, generated during the processing of biomass for other products (e.g. bagasse from sugar production from sugarcane, sawdust from the milling of forest products). These resources are generally concentrated at a processing operation.
- (c) Tertiary residues, produced from “wastes” (e.g. used cooking oil, organic fraction of municipal solid waste, reclaimed timber products).

Production systems for most of the annual crops used for bioenergy are well developed, as these crops have established uses for food and feed. Some biomass sources (e.g. residues from forest harvest operations) are obtained through modification of existing systems. Additionally, bioenergy demand is encouraging the development of new crops (such as jatropha (*Jatropha curcas*) and miscanthus (*Miscanthus* spp.)), and new production systems such as short rotation tree crops (including willow (*Salix* spp.), polar (*Populus* spp.) and eucalypts), which are sometimes coppiced.

16.5 Biomass Production and Implications for Soil Health

Soil health is a function of the complex interaction of chemical, physical and biological properties. Achieving significant bioenergy targets is likely to require large areas of land (Berndes et al. 2003) and increased production intensity (Pimentel et al. 2009), to increase biomass yields (Fischer et al. 2009). The impacts of bioenergy systems on soil health will depend on:

- LUC – that is, replacement of the previous land use (Luyssaert et al. 2008);
- The type of biomass production system introduced (e.g. annual or perennial);
- Management practices applied to the biomass system.

Impacts of bioenergy systems based on conventional annual crops and forestry are similar to other annual cropping and forestry systems, reviewed in Chaps. 9 and 12, respectively, and we do not address these topics further in this chapter. Generally annual plants require greater inputs and more frequent soil disturbance than perennial systems, which may be replanted after harvest at 5–10 years, or even less frequently if coppiced. Thus, annual systems are likely to pose a greater risk than perennials to soil health.

The anticipated increase in scale and intensity of biomass productions systems will increase pressure on natural resources and test the resilience of the biophysical systems. Options for increased biomass production, and management of their impacts on soil health, are discussed in Sect. 16.6.

In this section, we outline the anticipated impacts of biomass production systems on soil properties and processes that can influence soil health. While there has been little research reported on this topic, we can predict the probable impacts of these bioenergy systems from knowledge of the factors influencing soil health.

16.5.1 Soil Organic Matter

Soil organic matter (SOM) strongly influences many soil properties and as such is a primary indicator of soil health (see Chap. 5). The amount of SOM in soil is a function of climate, topography, parent material, biology and time (Rice 2005). SOM is generally higher in cool climate forests and wetlands where growth is considerable but soil biota activity limited. Conversely, SOM is lower in the wet tropics where it is rapidly mineralised, and lowest in dry environments where plant growth (and therefore input of organic matter) is limited by water availability (Bolin et al. 2000).

Maintaining SOM levels is a significant challenge to the sustainability of bioenergy systems where they increase biomass removal and/or have greater soil disturbance compared to conventional cropping systems. However, where bioenergy systems use degraded or marginal land, or involve establishment of perennial tree crops on intensively cultivated land, then SOM may be increased (Lasch et al. 2010).

Carbon is the major constituent of SOM; therefore changes in SOM have significant implications for climate change. Figure 16.2 shows the respective carbon pools and fluxes and potential impact of management in a forest-based bioenergy system.

It has been suggested that loss of soil carbon in the establishment of energy crops, or as a result of residue removal, could negate the climate change benefits of using bioenergy to displace fossil energy sources (Fargione et al. 2008). Cherubini

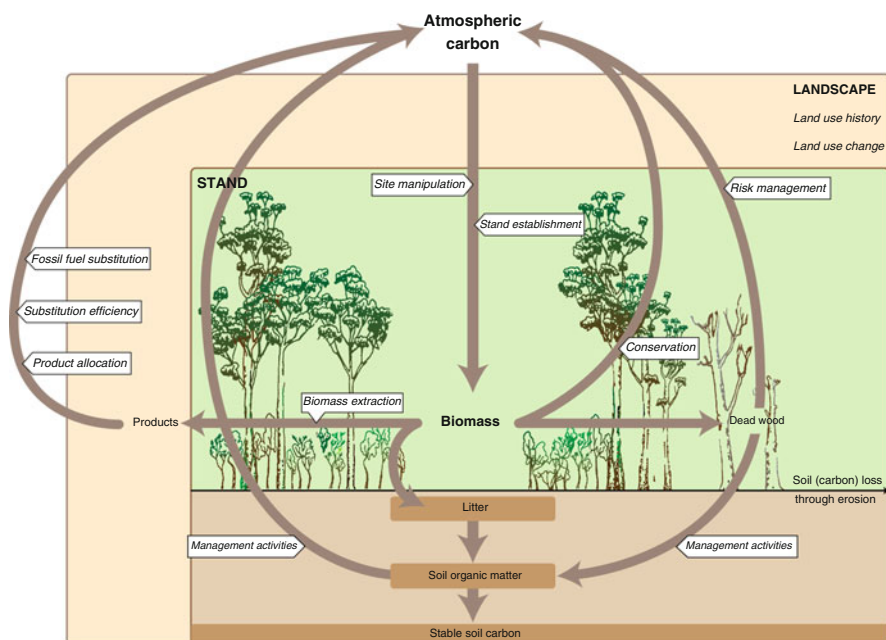


Fig. 16.2 The forms of atmospheric and terrestrial carbon as stocks (*boxes*) and flows (*arrows*) in a forest-based bioenergy system. Management options will impact on the respective flows and stocks of carbon and significantly influence soil health depending on disturbance, additions and subtractions to the soil system. Adapted from Bottcher and Lindner (2010)

and Ulgiati (2010) calculated that the loss of soil carbon contributed approximately 50% of total GHG emissions in the growing of biomass for the production and use of pellets for heat and electricity from corn stover and wheat straw, while Brandão et al. (2011) calculated that loss of soil carbon contributed $\approx 30\%$ of the emissions due to the production of rapeseed. However, Cowie et al. (2006) determined that for three forest systems in Australia [viz. short rotation eucalypts (*E. globulus*), pine (*P. radiata*) and sawlog eucalypt (*E. grandis*)], the losses of soil carbon were minor compared with the avoided GHG emissions from equivalent fossil fuel use. Similarly, small losses of soil carbon, or even gains, have been reported where perennial low-intensity bioenergy crops including switchgrass (*Panicum virgatum* L.) (Liebig et al. 2005), poplar and miscanthus (Borzecka-Walker et al. 2008) have replaced existing cultivated cropping systems. Impacts of sugarcane on soil carbon vary from losses to gains and are influenced by management; soil carbon is higher where cane is not burned before harvest, and where trash is retained (Cerri et al. 2011; Galdos et al. 2009; Pinheiro et al. 2010).

The loss or gain of soil carbon in a bioenergy system is difficult to assess due to the spatial and temporal variability of soil carbon (Coleman et al. 2004). It will be determined by the LUC, influenced by the species involved (which may differ in their proportional allocation of carbon belowground, and quality of litter

(Pritchard 2011), and the management applied (tillage frequency, proportion of residues removed). Where residues from annual crops are used, soil carbon loss can be significant. For example, Anderson-Teixeira et al. (2009) found that where 25–100% of the corn residue was harvested, soil organic carbon losses of 3–8 Mg ha⁻¹ occurred during the first 5 years. Conversely, Anderson-Teixeira et al (2009) reported a small increase in soil organic carbon (1 Mg ha⁻¹ year⁻¹ in the top 30 cm) in soil sustaining perennial grasses (including miscanthus and switchgrass). These results are consistent with data presented by Dawson and Smith (2007) where the ability of soil to sequester carbon was greater in perennial crops with reduced soil disturbance.

Perennial bioenergy systems that: (1) are established on already cleared agricultural land with minimal soil disturbance and (2) do not remove large amounts of residue will be more likely to retain soil carbon and improve soil health compared with annual cropping systems.

16.5.2 Soil Temperature

Soil temperature is an important factor influencing soil microbial activity (Pingingtha et al. 2010). The selection of plant species will influence the amount of radiation reaching the soil (through shading) and the speed of air movement, which will not only affect the soil temperature directly, but also indirectly through effect on the water content. Management of the bioenergy feedstock system such as the removal of straw or logging residues will increase the diurnal temperature fluctuation and impact microbial activity (Blanco-Canqui 2010; Blanco-Canqui and Lal 2009).

16.5.3 Soil Erosion

Soil erosion, by wind or water, has significant impact on soil health through loss of nutrients and soil carbon (Gregg and Izaurralde 2010; Pimentel 2006). This is of particular concern for energy crop production systems where frequent disturbance and removal of residues are likely to increase the risk of erosion (Blanco-Canqui 2010; Delucchi 2010). Furthermore, eroded soil can increase turbidity of streams and rivers (Tilman et al. 2002), and thus combined with eutrophication from nutrient run-off and leaching, bioenergy systems can reduce water quality (Brandão et al. 2011).

16.5.4 Soil Compaction

Operations involving heavy machinery, especially when the soil is wet, can lead to soil compaction (Blanco-Canqui and Lal 2009; Walmsley and Godbold 2010).

Compaction reduces soil porosity and infiltration, thus reducing available water for plant use, and increase waterlogging risk, leading to reduced mineralisation of soil carbon (Cowie et al. 2006). Removal of logging residues in forest-based bioenergy systems may increase soil compaction (Merino et al. 2004), causing reduction in soil health and inhibiting plant growth.

16.5.5 Soil Salinity

An excess of soluble salts, especially sodium, has negative effects on chemical and physical soil properties, and inhibits microbial activity and plant growth (Rengasamy 2006). One of the main drivers for the nascent bioenergy industry in Australia is the potential for an economically viable production system incorporating deep-rooted woody crops to capture and use available soil water to minimise waterlogging and control dryland salinity (Bartle et al. 2007; Crosbie et al. 2007). However, such crops must be carefully sited to avoid negative impacts through reduced streamflow and recharge of aquifers (Benyon et al. 2007; Jackson et al. 2005; Vertessy et al. 2003).

16.5.6 Nutrient Balance and Availability

The production and removal of biomass for bioenergy can significantly impact on chemical fertility through changing the nutrient balance in the soil. The balance of macronutrients (viz. N, P, K, Mg and Ca) and micronutrients (including S, Zn, Fe, Mn and B) is important in all production systems; nutrients removed in harvested biomass or through erosion, run-off and leaching must be replaced to avoid long-term decline in productivity (Blanco-Canqui and Lal 2009; Cowie et al. 2006; Gregg and Izaurralde 2010; Lal 2004). Loss of chemical fertility will limit plant growth, leading to reduced organic matter input and consequently lower microbial activity, nutrient and moisture retention.

Reduced nutrient availability will lead to declining productivity where biomass is continually removed, such as in proposed bioenergy cropping systems including SRWC (Blanco-Canqui 2010; Dickmann 2006; Merino et al. 2004; Sartori et al. 2007) and traditional agricultural crops (Blanco-Canqui and Lal 2009; Muller 2009). The effect of nutrient removal is complicated by the selective nutrient extraction from soil of the respective crops as well as what component of the biomass is removed. Bioenergy systems that remove green foliage (which is particularly high in N, P and K), or bark (which is high in Ca), have a higher risk of nutrient depletion (Cowie et al. 2006). Impacts will differ between species and nutrient removal will be lower in systems using deciduous species or straw harvested after plant maturity.

In their review of the impact of the removal of stover in corn production systems in the USA, Blanco-Canqui and Lal (2009) found that at some sites nitrogen declined and other nutrients remained steady, while at other sites all measured nutrients declined. It is clear that biomass removal will have a significant effect on soil nutrients, particularly nitrogen, and therefore soil health.

LUC can significantly affect the amount and form of nitrogen in the soil. For example, where pasture is converted to a plantation, site preparation will encourage mineralisation of organic matter, releasing nitrogen, which may be lost through leaching in the early stages of plantation growth before the tree roots have fully occupied the site (Kirschbaum et al. 2008; Turner and Lambert 2000).

It is important to consider the fate of the biomass if not removed for bioenergy. In some forest systems residues are windrowed and burned. This practice removes the majority of the carbon, and a large proportion of nitrogen, though the non-volatile nutrients will be retained. In this scenario, removal of residues for bioenergy will have less impact on the soil nutrient (and carbon) status. The retention of sugarcane green trash at harvest can significantly increase soil carbon and nitrogen (Pinheiro et al. 2010) though much of the retained trash decomposes within a year (Robertson and Thorburn 2007).

The ability to definitively determine how much of the residue can be removed without jeopardising soil health in different soil types, crops and management systems remains weak. However, Blanco-Canqui and Lal (2009) suggest that fertility decline is likely if >50% residue is removed from annual crop systems. Ensuring that nutrient-rich leaf material is retained on site (such as by harvesting after leaf fall, or leaving cut branches to dry in the field) is important to maintaining soil fertility (Fung et al. 2002; Walmsley and Godbold 2010).

16.5.7 Biological Activity and Impacts

The presence and activity of soil biota are fundamental to the development and maintenance of soil health (see Chap. 8). In turn, biological activity is influenced by the soil chemical and physical properties, especially porosity, range in moisture content, presence of toxic substances, temperature variation and the availability of nutrients. In addition, SOM provides significant energy for microbial activity. Bioenergy systems that reduce organic matter inputs, for example through increased intensity of biomass harvest, may therefore inhibit microbial activity.

Organic matter is decomposed through comminution and mineralisation, which are dependent on the activity of soil fauna and micro-organisms (Cogle et al. 1995). When land is converted from crop or pasture to forest, the increased shading of the soil surface can reduce surface temperatures, lowering microbial activity and retarding the litter decomposition rate (Grove et al. 2001). This increases the carbon stock in litter while decreasing input to the soil carbon pool. Conversely, reducing tillage disturbance and increasing organic matter and nitrogen (via fertilisation) in soil leads to increased microbial populations (Vargas Gil et al. 2009). There is some

“competition” between the respective processes; the balance determines whether microbial activity will be increased or decreased.

Perennial bioenergy systems, with reduced disturbance and increased input of root organic matter, are likely to encourage microbial activity compared with conventionally tilled annual crops. However, even where organic matter is returned to the soil, the impact on biological activity can vary. For example, Smolander et al. (2010) found that the impact of removal of logging residues on microbial processes was greater on low fertility sites.

Understanding the impacts on soil microbes of management options such as plant selection and cultivation, through altered temperature fluxes, retention and incorporation of organic matter, and soil disturbance regimes, is important to maintaining soil health under bioenergy systems.

16.6 Management Options

Realising the anticipated potential for bioenergy will require intensification of biomass production from existing agricultural and forest systems and expansion of the area used for biomass production. Managing environmental impacts is considered one of the most challenging aspects of biomass production on a large scale (Delucchi 2010; Pimentel et al. 2009).

In this section, we consider the impacts on soil health of intensification, including through use of fertiliser, and discuss management options to minimise these impacts. We discuss the implications of expansion of area used for bioenergy in Sect. 16.7.

16.6.1 Use of Marginal and Degraded Land

Currently much of the biomass feedstock for transport fuels is produced from conventional agricultural crops grown on prime agricultural lands. For example, the US ethanol industry is largely based on corn production in the mid-west (Solomon 2010). There is direct competition between the biomass feedstock for energy with food or feed. This leads to concern and debate regarding food and energy security and respective national interests (Pimentel et al. 2009). In addressing these concerns, there is significant opportunity for bioenergy feedstocks to be produced on degraded and marginal lands (Bartle et al. 2007; Delucchi 2010; Tilman et al. 2006; Tilman et al. 2009). While such land is not well suited to conventional crops, it may be satisfactory for lignocellulosic crops such as giant reed (*Arundo donax*), or tree crops such as jatropha, that are reputed to tolerate dry, infertile environments (Jongschaap et al. 2007). Low-input perennial grass systems that increase the opportunity for plant and animal diversity have also been suggested for North America (Tilman et al. 2006). While these species may survive

in harsh environments, yields will inevitably be low. Nevertheless, the potential for production of lignocellulosic feedstocks on marginal lands is significant, with estimates of biomass yields capable of meeting up to 10 EJ year⁻¹ of global energy requirements (Bauen et al. 2010). It is critical that sustainable land management practices are used to minimise risk to soil health on marginal lands, which can be particularly susceptible to degradation.

There is also potential that use of degraded lands for bioenergy production could deliver substantial net mitigation compared with fossil fuel production and consumption. For example, Wicke et al (2011) demonstrated that degraded lands in Indonesia dominated by the grass weed *Imperata cylindrica* can be used effectively for oil palm production. Use of degraded land often depleted in SOM and nutrients could enhance soil health, as growing plants contribute organic matter and stimulate microbial activity and nutrient cycling. However, establishment of bioenergy crops may be challenging as soil constraints must be overcome.

16.6.2 Intensification

Intensifying production from the current land base, through use of increased inputs, such as fertiliser (discussed below) or irrigation could significantly increase biomass production, particularly in regions such as Africa where yields are well below global averages. However, if larger production per unit time and/or per unit area is to be sustainably achieved, then careful selection of species, inputs and management will be necessary.

Impacts on soil health from intensified production are likely to occur on-site (at a local scale) through direct effects on soil properties, and could include: increase in soil bulk density due to compaction from harvesting operations; nutrient imbalances due to biomass removal; increased mineralisation of soil carbon from site disturbance; and changes to evapotranspiration and soil temperature (e.g. where plantations replace pastures). The magnitude of these direct effects depends on the pre-existing soil conditions, and the previous and new species and production systems. Irrigation offers the capacity to reduce moisture limitations, but can increase the risk to soil health through potential for salinisation if not managed to minimise deep drainage (Rengasamy 2006). Bioenergy feedstocks may be derived from crop residues in irrigated areas (e.g. rice husk, sugarcane trash), but it is unlikely that dedicated energy crops will be grown under irrigation due to high cost of water and higher value of alternative crops.

We know that intensive cropping leads to reduced soil carbon (Dalal and Chan 2001; Tilman et al. 2002). And though this is often attributed simply to soil disturbance (leading to disruption of soil aggregates and increased mineralisation of protected organic matter), there is evidence that soil erosion and decreased input of organic matter are also significant (Cowie et al. 2006; Paul et al. 2002). Thus, cropping generally decreases soil carbon through a combination of reduced input

and enhanced loss. Therefore, intensification of biomass production is likely to exacerbate soil carbon decline, thus reducing soil health.

However, there are opportunities, through intensification, for integrated production of biomass for energy and food or feed, while preserving or enhancing soil health (Dale et al. 2010). One example is the use of SRWC such as oil mallees (e.g. *Eucalyptus polybractea*). Oil mallees have been planted in belts across wheat fields and require lower inputs and less frequent soil disturbance than conventional annual crops (Bartle et al. 2007; Hobbs et al. 2009).

16.6.3 Fertiliser

Increased application of fertiliser is one significant management option used in intensive production systems to increase biomass production. Where soils are deficient in specific plant nutrients, for example phosphorus in many Australian soils (Holford 1997), or where harvest or residue removal leads to nutrient imbalances and limitations (Blanco-Canqui and Lal 2009; Cowie et al. 2006; Grigal 2000; Sartori et al. 2007), fertiliser application becomes critical to maintaining plant production. Fertiliser application stimulates plant growth through increased nutrient supply, and can lead to additional biomass input to soil. But this does not necessarily result in higher soil carbon stocks, as SOM mineralisation may also be enhanced (Khan et al. 2007).

Many agricultural systems rely on fertiliser to support increased plant growth; however, globally the efficiency of fertiliser use has declined over the last 50 years (Tilman et al. 2002). For optimum efficiency site-specific management of fertilisers is essential, matching rate and timing of application to plant uptake (Jalali 2007). There is a GHG emissions cost to fertiliser production (Wood and Cowie 2004), and application of nitrogen fertilisers leads to increased flux of N_2O from soils (Stehfest and Bouwman 2006). Thus, increased use of fertilisers in biomass production reduces the climate change mitigation benefits of bioenergy.

Currently most transport biofuels are derived from corn (in the USA), sugarcane (in Brazil) and rapeseed oil (Europe) (Solomon 2010). This biomass is grown in intensively managed production systems with significant inputs, including high fertiliser rates, leading to high yields. The expectation of increased use of lignocellulosic components of biomass for energy (Richard 2010) means that alternative crops and harvest systems will be used in the future to provide feedstocks (e.g. Bartle and Abadi 2010). These crops and their management may differ significantly from current large-scale bioenergy production; the perennial grass and tree crop systems being developed have reduced disturbance (i.e. less frequent tillage) and potentially lower fertiliser requirements. However, fast growing, short rotation biomass plantations will require higher fertiliser inputs than conventional forestry to maximise biomass production and minimise decline in nutrient status. This increased fertiliser use could jeopardise future productivity and soil carbon stocks (Turner and Lambert 2000).

In the search for sustainable biomass production systems, mixed species, in contrast to monocultures, may be beneficial. For example, mixing species and including nitrogen fixers may have greater productivity and reduced need for fertiliser application (Richards et al. 2010). Finding the optimal species mix, while conceptually straightforward (Forrester et al. 2005), will require field trials of potentially promising species and management systems. Another option is to use organic amendments replacing synthetic fertiliser, ensuring the recycling of nutrients from processing and post-consumer residues, including biosolids (Wang et al. 2008).

16.6.4 Biochar

Biochar is a co-product of the bioenergy technology pyrolysis in which biomass is heated in the absence of oxygen. Besides bioenergy, this process can simultaneously produce biochar that can be used beneficially as a soil amendment. Biochar is highly recalcitrant, lasting potentially hundreds to thousands of years in soil (Singh and Cowie 2010). The potential for biochar as a soil amendment is discussed in detail by Waters et al. (See Chap. 15).

The biomass feedstock and pyrolysis conditions determine the physicochemical characteristics of the biochar, and therefore its value as a soil amendment and fertiliser (see Chap. 15). The application of biochar, depending on its properties, can not only increase soil carbon and cation exchange capacity, but also enhance physical properties such as aggregate stability and water-holding capacity. In turn, these changes to physicochemical properties can enhance biological activity, contributing to nutrient cycling and disease suppression (Warnock et al. 2007).

In addition to the benefits of delayed decomposition of organic matter and the supply of renewable energy, biochar can contribute to climate change mitigation through reduction in fertiliser requirements, decreased N₂O emissions from soil and enhanced plant growth (see Chap. 15). Woolf et al. (2010) estimate that the production and use of biochar could reduce global GHG emissions by 12% of current anthropogenic CO₂-e (some 1.8 Gt CO₂-e per annum), with 50% of the reduction from carbon sequestration, 30% from replacement of fossil fuel energy and 20% from avoided emissions of methane and N₂O.

In previous sections, we have discussed the risk that production of biomass crops, and collection of in-field residues for bioenergy, could reduce soil health. That is, we have highlighted the trade-off between maximising organic inputs to soil, to support maintenance of soil health, and removal of biomass for use as a renewable energy source to mitigate climate change. However, through pyrolysis there is potential to simultaneously produce renewable fuel, and biochar that can be used to maintain and/or enhance soil health. The net mitigation of a biochar system could be greater than if the same biomass had been used solely for bioenergy (Woolf et al. 2010). However, this assertion requires confirmation through further research to quantify, for example, the impact of different biochars on N₂O emissions. Furthermore, the conclusions of Woolf et al. (2010) may be true only

for specific feedstocks, and where less GHG-intensive fossil energy sources are used. For example, if electricity is supplied from GHG-intensive brown coal at 1.2 kg CO₂-e per kWh (Commonwealth of Australia 2010), then greater mitigation may be achieved using all available biomass for energy. However, where natural gas is the fossil energy source, releasing 0.7 kg CO₂-e per kWh (Integrated Sustainability Analysis 2006), use for biochar production may achieve greater reduction in GHG emissions.

16.7 Indirect Impacts of Bioenergy Systems on Soil Health

Policies that encourage bioenergy are likely to lead to the expansion of land devoted to biomass production. This will entail LUC, that is, conversion from existing uses to biomass production. In already cultivated land, there may be minimal impact where one annual crop is replaced by another. However, LUC could result in conversion of pasture or forest to annual crops, which will directly impact on soil health and especially soil carbon as discussed above (see Chap. 9). Furthermore, the replacement of conventional land uses by biomass production may lead to iLUC: relocation of the displaced industry may result *indirectly* in conversion from forest to agricultural uses. The clearing of forested areas can lead to significant release of carbon into the atmosphere (Bolin et al. 2000; Delucchi 2010; Schlamadinger et al. 2007) and can significantly impact on soil health.

Indirect LUC is an issue associated with the development of various large-scale bioenergy systems including the production of palm oil in tropical countries (Laurance et al. 2010). Another controversial example of iLUC is deforestation in Brazil that is attributed to increased crop production for bioenergy (Fargione et al. 2008; Morton et al. 2006; Pimentel and Patzek 2007). In this situation, a global driver, which is strong markets for biofuels feedstocks, such as soybeans, and processed biofuels (ethanol), leads to local-scale changes with implications for soil health. For example, in Brazil sugarcane and soybeans are replacing pasture, and consequently cattle ranching displaced from pastureland could encroach on forest areas. The resulting deforestation can lead to large SOM loss through oxidation and erosion. Release of soil carbon to the atmosphere can negate the benefits from displacing mineral petroleum use (Fargione et al. 2008; Searchinger et al. 2008). In Brazil, better integration of existing land uses and co-utilisation of feedstocks (e.g. steam cooked bagasse pulp) for energy and feed production are proposed ways of integrating production systems and reducing iLUC (Sparovek et al. 2007, 2009).

The GHG emissions implications of iLUC and attribution to bioenergy are difficult to quantify (Plevin et al. 2010). Nevertheless, policymakers are developing mechanisms that will include estimates of iLUC when calculating the mitigation benefits of bioenergy (European Parliament 2009). Policies have also been introduced to minimise the risk of LUC. One such mechanism is the use of legislation to minimise clearing of native vegetation, which may be implemented for multiple reasons including the protection of biodiversity rather than specifically to

address climate change (e.g. the Native Vegetation Act (2003) in New South Wales, Australia). A market-based incentive remains critical to promote development of a large-scale bioenergy industry with minimum GHG footprint (Stern 2007).

16.8 Managing and Regulating the Impacts of Bioenergy Production

Bioenergy systems will need to deliver on current policy-defined expectations such as reducing the emissions of GHGs or minimising environmental impacts and enhancing social outcomes (e.g. enhancing regional development and increasing trade opportunities). Meeting GHG targets and obligations is particularly important if a price (that is effectively “artificial”) for carbon is established to address the externalities outlined by Stern (2007).

There are many mechanisms being established around the world that aim to improve sustainability of bioenergy systems. Most sustainability schemes are underpinned by agreed *principles* that are expounded as *criteria* and measured with stated *indicators*. Many of these developing systems are based on the earlier work of Cramer et al. (2006), who followed the “triple P approach” focussing on people, planet and profit to develop six themes for consideration in developing sustainability criteria (Cramer et al. 2006):

- Social well-being;
- Competition with food, local energy supply, medicines and building materials;
- Environment;
- Biodiversity;
- GHG balance;
- Economic prosperity.

To gain market access, bioenergy projects will need to demonstrate compliance with the criteria developed in applicable sustainability schemes. The formalisation of the *criteria* and *indicator* approach is achieved via the implementation of certification schemes that involve third-party verification of compliance. Although the approach of developing sustainability systems based on clear *principles* and *criteria* adds costs to biomass production, these schemes should increase consumer confidence (O’Connell et al. 2009).

We expect that over the next 10 years, there will be ongoing discussion and refinement of existing criteria-based systems for the production of sustainable biomass for energy production. Currently, initiatives include some specific to certain industries (e.g. the Roundtable on Sustainable Palm Oil (RSPO) production; the Roundtable on Responsible Soy; and the Better Sugarcane Initiative). These initiatives, detailed by O’Connell et al. (2009) and Vis et al. (2008), are driven by proponents wanting to support sustainable development of their industries. Larger independent systems are also being developed. These initiatives, including the United Nations Commission on Sustainable Development-sponsored Global

Bioenergy Partnership (GBEP) and the Swiss-led Roundtable on Sustainable Biofuels (RSB), are not feedstock specific. The GBEP is particularly targeted at developing nations (United Nations 2008) and like the RSB aims to identify key *principles* and *criteria* for consideration via a systematic assessment as outlined by van Dam et al. (2008). Using the RSB as an example, Table 16.1 shows the link between the respective *principles* and the three tenets of sustainability espoused

Table 16.1 The Roundtable for Sustainable Biofuels (RSB) principles as an example of the key issues in development of sustainability certification systems for bioenergy production

Roundtable for Sustainable Biofuel Principle	Sustainability tenet
Legality	Social
Biofuel operations shall follow all applicable laws and regulations	
Planning, monitoring and continuous improvement	Economic
Sustainable biofuel operations shall be planned, implemented and continuously improved through an open, transparent and consultative impact assessment and management process and an economic viability analysis	Environmental
Greenhouse gas emissions	Environmental
Biofuels shall contribute to climate change mitigation by significantly reducing life cycle GHG emissions as compared to fossil fuels	
Human and labour rights	Social
Biofuel operations shall not violate human rights or labour rights, and shall promote decent work and the well-being of workers	
Rural and social	Social
In regions of poverty, biofuel operations shall contribute to the social and economic development of local, rural and indigenous people and communities	Economic
Local food security	Social
Biofuel operations shall ensure the human right to adequate food and improve food security in food insecure regions	
Conservation	Environmental
Biofuel operations shall avoid negative impacts on biodiversity, ecosystems and other conservation values	
Soil	Environmental
Biofuel operations shall implement practices that seek to reverse soil degradation and/or maintain soil health	
Water	Environmental
Biofuel operations shall maintain or enhance the quality and quantity of surface and ground water resources, and respect prior formal or customary water rights	
Air	Environmental
Air pollution from biofuel operations shall be minimised along the supply chain	
Use of technology, inputs and management of waste	Social
The use of technologies in biofuel operations shall seek to maximise production efficiency and social and environmental performance, and minimise the risk of damages to the environment and people	Environmental
Land rights	Social
Biofuel operations shall respect land rights and land use rights	

by Cramer et al. (2006). Soil health is nominated specifically as an issue for sustainability of bioenergy systems, in Principle 8 Soil in Table 16.1, and criteria for assessment of compliance have been agreed (Roundtable on Sustainable Biofuels 2009).

Currently many sustainability schemes are voluntary and are used in product differentiation. However, in line with increased societal expectations, some jurisdictions are legislating the production and consumption of bioenergy, especially biofuels that meet nominated sustainability criteria. For example, in the European Union recent legislation requires biofuels to meet thresholds for minimum GHG mitigation and precludes use of biomass from biodiverse lands (European Parliament 2009); in Australia, the State of New South Wales legislated the mandatory use of ethanol and biodiesel, and the supply of these biofuels must comply with sustainability criteria (New South Wales 2007). Maintaining free trade between countries may become an issue in the application of criteria-based systems that could be construed as blocking the exchange of goods (Buchholz et al. 2009; Delzeit and Holm-Muller 2009; Lewandowski and Faaij 2006). van Dam et al. (2008) discuss, in detail, the interaction between the establishment of sustainability criteria and trade especially with respect to the General Agreement on Tariffs and Trade (GATT) and the World Trade Organization (WTO).

While current policy direction aims to improve sustainability of bioenergy systems, many challenges remain in meeting the demand for renewable energy while addressing environmental and social objectives at local, regional, national and international scales (Florin and Bunting 2009; Reinhard and Zah 2009). The application of the respective systems in different countries (with varying levels of governance), large variation in climate and edaphic conditions, multiple land use, crop and product outcomes will challenge the application and compliance of developed sustainability systems. Reports of the successful application of systems are scarce (e.g. Froger et al. 2010), but with the need to develop confidence and allow trade of biomass for energy and biofuels, significant effort is underway.

It is interesting to note that the sustainability requirements being demanded of bioenergy exceed the general expectations of other land uses in many cases. Maintenance of soil health is generally not legislated for food and fibre production systems, nor is avoidance of iLUC. O'Connell et al. (2009) indicate *there are outstanding issues to be resolved around the burden of proof of sustainability being placed on bioenergy especially in situations where land and water resources are shared between many production systems; the drivers for LUC are many-fold and the causal linkages to indirect effects are not clear*. The introduction of sustainability certification is critical but challenging, and significant development, testing and discussion are required to obtain solutions that allow for local interpretation of globally agreed principles and criteria (Florin and Bunting 2009; Hennenberg et al. 2010; O'Connell et al. 2009; Sparovek et al. 2007). It is likely that the debate over sustainability of biomass production for bioenergy will lead to calls for certification of food and fibre production systems that should include expectations of maintenance of soil health.

16.9 Summary and Conclusions

As the world searches for low-carbon renewable energy, there will be significant opportunities for biomass to provide heat, electricity and transport fuels. Bioenergy can contribute to climate change mitigation through increasing sequestration of carbon (e.g. in forests) and through reducing use of fossil fuels. With various feedstocks and process routes and multiple products, there are many bioenergy options that can produce not only energy but also other products, such as biochar, that may enhance the economic, social and environmental role of bioenergy. Bioenergy could supply greater than 30% of world primary energy demands by 2050. However, questions remain concerning the capacity and sustainability of large-scale intensive biomass energy systems (Muller 2009), particularly over implications for soil health.

Soil health is a function of the interaction between the inherent soil type, climate and the management of the bioenergy system. The impacts on soil health will be determined by the current land use, the bioenergy system that replaces it and the management practices applied. Biomass for bioenergy can be obtained from residues from conventional crop and forestry systems which, depending on the pre-existing land use and subsequent management of the bioenergy crop, may have negative impacts on soil health. Alternatively biomass can be produced from purpose-grown energy crops. Where these can be grown on marginal and degraded land, they may improve soil health. However, if they are grown on land that was previously used for cropping or grazing, their conversion to bioenergy crops is likely to lead to iLUC. This is likely to have negative impacts on soil health, with further negative consequences for managing climate change. To meet demand, it is likely that the area devoted to biomass production will expand, using productive land as well as marginal and/or degraded land, which will impact directly on physical, chemical and biological aspects of soil health. Where degraded lands are revegetated, that may have a positive impact on soil health.

If bioenergy is to effectively contribute to climate change mitigation, then it needs to have a positive energy balance, displace the use of fossil fuels for energy and potentially sequester carbon in biomass and soil. Understanding the role of soil carbon and the impact of land use, crop selection and management on soil health is critical to the long-term sustainability of existing and proposed bioenergy feedstock systems. As an important determinant of soil health, the risk of depletion of soil carbon stocks in biomass systems, due to the larger proportion of organic matter and nutrients that are removed from the site, compared with conventional grain, forage and timber production systems, needs to be carefully managed. By avoiding significant disturbance, balancing nutrient inputs and removals, and protecting soil from erosion, soil carbon can be maintained or enhanced. It is likely that in many systems (e.g. where woody plantations replace pastures), there may be an initial decline in soil carbon. But in well-managed systems, this decline will be significantly smaller than the GHG mitigation benefit of avoided fossil fuel emissions.

Other physicochemical and biological aspects of soil health need to be considered as bioenergy feedstock production increases in scale and intensity. The impact

on the hydrological cycle can be significant; from affecting the infiltration of water into the soil and the soil water-holding capacity, to regional-scale impacts on streams and rivers. The increased use of fertiliser may lead to pollution problems such as eutrophication, and release of N_2O – a potent GHG. This, coupled with the extraction of biomass, can impact on the nutrient balance in the soil and pH leading to a decline in soil health. Many impacts are interrelated and can lead to significant long-term changes to the soil health from which it may take decades to recover. Maintenance of soil fertility will remain challenging, especially in systems where the majority of the biomass is removed for processing.

The expansion of biomass production for energy needs to be managed, to reduce potential negative impacts through:

- Minimising the extent of direct LUC;
- Reducing the risk of indirect LUC;
- Judicious selection of suitable crops;
- Adaptive management with consideration of economic goals in conjunction with social and environmental values.

Government, industry and land managers have specific roles: in providing guidelines for development; balanced system selection and responsive, site-specific management, respectively. To give confidence to industry and society that bioenergy is not only helping to meet energy needs but also reaching other goals, several sustainability frameworks are being developed. The most robust of these rely on the development of clear principles that are supported by succinct criteria and reported using agreed indicators. We expect that these systems will continue to develop and be tested over the next decade. They provide a clear message to bioenergy feedstock producers and processors that for large-scale production to occur, society needs to be confident that environmental and social goals are considered. This is particularly true in relation to soil health.

Maintaining soil health in biomass production systems is fundamental to sustaining yields and meeting goals such as climate change mitigation and regional development, while minimising on- and off-site impacts. In developing sustainable biomass production systems, maintaining soil health will be a challenge, particularly as the intensity of production is increased to meet the anticipated demand for biomass for energy and other uses.

References

- ABARE (2010) Energy in Australia 2010. Australian Bureau of Agricultural and Resource Economics, Canberra
- Alm M, Cato J, Lundmark L, Myrman J, Raab U, Karlberg M, Karlsson T, Jöhnemark M, Bohnstedt S, Petersson K, Sahlin K, Berggren T, Bäck M, Sahlin M, Linder E, Bäck M, Wagman N, Sahlin M, Lindberg C, Parikka M, Kärmarck U, Veibäck E, Östensson E (2009) Energy in Sweden: facts and figures. Swedish Energy Agency, Stockholm

- Anderson-Teixeira KJ, Davis SC, Masters MD, Delucia EH (2009) Changes in soil organic carbon under biofuel crops. *Glob Change Biol Bioenergy* 1(1):75–96
- Baffes J, Haniotis T (2010) Placing the 2006/08 commodity price boom into perspective. The World Bank, Washington
- Bartle J, Abadi A (2010) Toward sustainable production of second generation bioenergy feedstocks. *Energy Fuels* 24:2–9
- Bartle J, Olsen G, Cooper D, Hobbs T (2007) Scale of biomass production from new woody crops for salinity control in dryland agriculture in Australia. *Int J Global Energy Issues* 27(2):115–137
- Bauen A, Berndes G, Junginger M, Londo M, Vuille F, Ball R, Bole T, Chudziak C, Faaij A, Mozaffarian H (2010) Bioenergy – a sustainable and reliable energy source. A review of status and prospects. IEA Bioenergy, Petten
- Benyon R, England J, Eastham J, Polglase P, White D (2007) Tree water use in forestry compared to other dry-land agricultural crops in the Victorian context. CSIRO, Canberra
- Berndes G, Hoogwijk M, van den Broek R (2003) The contribution of biomass in the future global energy supply: a review of 17 studies. *Biomass Bioenergy* 25(1):1–28
- Berndes G, Hansson J, Egeskog A, Johnsson F (2010) Strategies for 2nd generation biofuels in EU – co-firing to stimulate feedstock supply development and process integration to improve energy efficiency and economic competitiveness. *Biomass Bioenergy* 34(2):227–236
- Bernotat K, Sandberg T (2004) Biomass fired small-scale CHP in Sweden and the Baltic States: a case study on the potential of clustered dwellings. *Biomass Bioenergy* 27(6):521–530
- Blanco-Canqui H (2010) Energy crops and their implications on soil and environment. *Agron J* 102(2):403–419
- Blanco-Canqui H, Lal R (2009) Crop residue removal impacts on soil productivity and environmental quality. *Crit Rev Plant Sci* 28(3):139–163
- Bolin B, Sukumar R, Ciais P, Cramer W, Jarvis P, Kheshgi H, Nobre C, Semenov S, Steffen W (2000) Global perspective. In: Watson R, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ (eds) Land use, land-use change, and forestry: a special report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 23–51
- Borzecka-Walker M, Faber A, Borek R (2008) Evaluation of carbon sequestration in energetic crops (*Miscanthus* and coppice willow). *Int Agrophys* 22(3):185–190
- Bottcher H, Lindner M (2010) Managing forest plantations for carbon sequestration today and in the future. In: Bauhus J, Van der Meer P, Kanninen M (eds) Ecosystem goods and services from plantation forests. Earthscan, London, pp 43–76
- Brandão M, Milà Canals L, Clift R (2011) Soil organic carbon changes in the cultivation of energy crops: implications for GHG balances and soil quality for use in LCA. *Biomass Bioenergy*. doi:10.1016/j.biombioe.2009.10.019:14
- Buchholz T, Luzadis VA, Volk TA (2009) Sustainability criteria for bioenergy systems: results from an expert survey. *J Cleaner Prod* 17(suppl 1):s86–s98
- Capon T, Harris M, Reeson A (2010) Soil carbon sequestration market based instruments (MBIs): a literature review. University of Sydney, Sydney
- Cayuela ML, Oenema O, Kuikman PJ, Bakker RR, van Groenigen JW (2010) Bioenergy by-products as soil amendments? Implications for carbon sequestration and greenhouse gas emissions. *Glob Change Biol Bioenergy* 2(4):201–213
- Cerri CC, Galdos MV, Maia SMF, Bernoux M, Feigl BJ, Powlson D, Cerri CEP (2011) Effect of sugarcane harvesting systems on soil carbon stocks in Brazil: an examination of existing data. *Eur J Soil Sci* 62(1):23–28
- Cherubini F (2010) The biorefinery concept: using biomass instead of oil for producing energy and chemicals. *Energy Convers Manage* 51(7):1412–1421
- Cherubini F, Ulgiati S (2010) Crop residues as raw materials for biorefinery systems – a LCA case study. *Appl Energy* 87(1):47–57
- Cogle AL, Reddy MVR, Rao KPC, Smith GD, McGarry D, Yule DF (1995) The role of biological practices and the soil biota in management of sealing, crusting and hardsetting soils. In: So HB,

- Smith GD, Raine SR, Schafer BM, Loch RJ (eds) Sealing, crusting and hardsetting soils: productivity and conservation. Australian Society of Soil Science (Queensland Branch), Brisbane, pp 305–324
- Coleman MD, Isebrands JG, Tolsted DN, Tolbert VR (2004) Comparing soil carbon of short rotation poplar plantations with agricultural crops and woodlots in North Central United States. *Environ Manage* 33(Suppl 1):S299–S308
- Commonwealth of Australia (2010) National greenhouse accounts (NGA) factors. Department of Climate Change and Energy Efficiency, Canberra
- Cowie AL, Smith P, Johnson D (2006) Does soil carbon loss in biomass production systems negate the greenhouse benefits of bioenergy? *Mitig Adapt Strateg Glob Change* 11(5/6):979–1002
- Cramer J, Wissema E, Lammers E, Dijk D, Jager H, van Bennekom S, Breunese E, Horster R, van Leenders C, Wolters W, Kip H, Stam H, Faaij A, Kwant K (2006) Criteria for sustainable biomass production. Project group ‘Sustainable production of biomass’ in the Energy Transition Task Force, Amsterdam
- Crosbie RS, Hughes JD, Friend J, Baldwin BJ (2007) Monitoring the hydrological impact of land use change in a small agricultural catchment affected by dryland salinity in central NSW, Australia. *Agric Water Manage* 88(1/3):43–53
- Dalal RC, Chan KY (2001) Soil organic matter in rainfed cropping systems of the Australian cereal belt. *Aust J Soil Res* 39:435–464
- Dale BE, Bals BD, Kim S, Eranki P (2010) Biofuels done right: land efficient animal feeds enable large environmental and energy benefits. *Environ Sci Technol* 44(22):8385–8389
- Dawson JJC, Smith P (2007) Carbon losses from soil and its consequences for land-use management. *Sci Total Environ* 382(2–3):165–190
- Delucchi MA (2010) Impacts of biofuels on climate change, water use, and land use. *Ann NY Acad Sci* 1195:28–45
- Delzeit R, Holm-Muller K (2009) Steps to discern sustainability criteria for a certification scheme of bioethanol in Brazil: approach and difficulties. *Energy* 34(5):662–668
- Dickmann DI (2006) Silviculture and biology of short-rotation woody crops in temperate regions: then and now. *Biomass Bioenergy* 30(8/9):696–705
- Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. *Appl Soil Ecol* 15(1):3–11
- Duer H, Christensen PO (2010) Socio-economic aspects of different biofuel development pathways. *Biomass Bioenergy* 34(2):237–243
- European Parliament (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/E. *Official J Eur Union L* 140:47
- Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. *Science* 319(5867):1235–1238
- Fischer G, Hizsnyik E, Prieler S, Shah M, van Velthuisen H (2009) Biofuels and food security. International Institute for Applied Systems Analysis, Vienna
- Fischer G, Prieler S, Velthuisen Hv, Berndes G, Faaij A, Londo M, Wit Md (2010) Biofuel production potentials in Europe: sustainable use of cultivated land and pastures, Part II: Land use scenarios. (Special Issue: a roadmap for biofuels in Europe.). *Biomass Bioenergy* 34(2):173–187
- Florentinus A, Hamelinck C, de Lint S, van Iersel S (2008) Worldwide potential of aquatic biomass. *Ecofys*, Utrecht
- Florin MV, Bunting C (2009) Risk governance guidelines for bioenergy policies. *J Cleaner Prod* 17(suppl 1):S106–S108
- Forrester DI, Bauhus J, Cowie AL (2005) On the success and failure of mixed-species tree plantations: lessons learned from a model system of *Eucalyptus globulus* and *Acacia mearnsii*. *For Ecol Manage* 209(1–2):147–155
- Friedlingstein P (2008) A steep road to climate stabilization. *Nature* 451(7176):297–298

- Fritsche UR, Hennenberg KJ, Hermann A, Hünecke K, Herrera R, Fehrenbach H, Roth E, Hennecke A, Giegrich J (2010) Development of strategies and sustainability standards for the certification of biomass for international trade. Federal Environment Agency, Dessau
- Froger E, Paz A, Vissers P (2010) Selection of a sustainability standard for pilot assessments of *Jatropha* producers in Mozambique. Partners for Innovation, Amsterdam
- Fung PYH, Kirschbaum MUF, Raison RJ, Stucley C (2002) The potential for bioenergy production from Australian forests, its contribution to national greenhouse targets and recent developments in conversion processes. *Biomass Bioenergy* 22(4):223–236
- Galdos MV, Cerri CC, Cerri CEP (2009) Soil carbon stocks under burned and unburned sugarcane in Brazil. *Geoderma* 153(3/4):347–352
- Gregg JS, Izaurrealde RC (2010) Effect of crop residue harvest on long-term crop yield, soil erosion and nutrient balance: trade-offs for a sustainable bioenergy feedstock. *Biofuels* 1(1):69–83
- Gregory JM, Jones CD, Cadule P, Friedlingstein P (2009) Quantifying carbon cycle feedbacks. *J Climate* 22(19):5232–5250
- Grigal DF (2000) Effects of extensive forest management on soil productivity. *For Ecol Manage* 138(1–3):167–185
- Grove TS, O’Connell AM, Mendham D, Barrow NJ, Rance SJ (2001) Sustaining the productivity of tree crops on agricultural land in South-Western Australia. Rural Industries Research & Development Corporation, Canberra
- Halleux H, Lassaux S, Renzoni R, Germain A (2008) Comparative life cycle assessment of two biofuels ethanol from sugar beet and rapeseed methyl ester. *Int J Life Cycle Assess* 13(3):184–190
- Hansson J, Berndes G (2009) Future bioenergy trade in the EU: modelling trading options from a cost-effectiveness perspective. *J Cleaner Prod* 17(suppl 1):s27–s36
- Hennenberg KJ, Dragisic C, Haye S, Hewson J, Semroc B, Savy C, Wiegmann K, Fehrenbach H, Fritsche UR (2010) The power of bioenergy-related standards to protect biodiversity. *Conserv Biol* 24(2):412–423
- Hobbs TJ, Bartle J, Bennell M, George BH (2009) Prioritisation of regional woody crop industries. In: Hobbs T (ed) Regional industry potential for woody biomass crops in lower rainfall southern Australia. Rural Industries Research & Development Corporation, Canberra, pp 5–38
- Holford ICR (1997) Soil phosphorus: its measurement, and its uptake by plants. *Aust J Soil Res* 35:227–240
- Hoogwijk M, Faaij A, Bd V, Turkenburg W (2009) Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. *Biomass Bioenergy* 33(1):26–43
- Integrated Sustainability Analysis (2006) Life-cycle energy balance and greenhouse gas emissions of nuclear energy in Australia. The University of Sydney, Sydney
- International Energy Agency (2009) World energy outlook 2009. OECD/IEA, Paris
- IPCC (2001) Working Group I: the scientific basis. Intergovernmental Panel on Climate Change, Cambridge
- Jackson RB, Jobbagy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, Farley KA, le Maitre DC, McCarl BA, Murray BC (2005) Trading water for carbon with biological carbon sequestration. *Science* 310(5756):1944–1947
- Jalali M (2007) Site-specific potassium application based on the fertilizer potassium availability index of soil. *Precision Agric* 8(4–5):199–211
- Jongschaap REE, Corre WJ, Bindrabin PS, Brandanberg WA (2007) Claims and facts on *Jatropha curcas* L. Plant Research International B.V, Wageningen
- Khan SA, Mulvaney RL, Ellsworth TR, Boast CW (2007) The myth of nitrogen fertilization for soil carbon sequestration. *J Environ Qual* 36(6):1821–1832
- Kirschbaum MUF, Guo LB, Gifford RM (2008) Why does rainfall affect the trend in soil carbon after converting pastures to forests? A possible explanation based on nitrogen dynamics. *For Ecol Manage* 255(7):2990–3000
- Lal R (2004) Soil carbon sequestration to mitigate climate change. *Geoderma* 123(1–2):1–22

- Lal R, Follett RF, Kimble JM (2003) Achieving soil carbon sequestration in the United States: a challenge to the policy makers. *Soil Sci* 168(12):827–845
- Lasch P, Kollas C, Rock J, Suckow F (2010) Potentials and impacts of short-rotation coppice plantation with aspen in Eastern Germany under conditions of climate change. *Reg Environ Change* 10(2):83–94
- Lattimore B, Smith CT, Titus BD, Stupak I, Egnell G (2009) Environmental factors in woodfuel production: opportunities, risks, and criteria and indicators for sustainable practices. *Biomass Bioenergy* 33(10):1321–1342
- Laurance WF, Koh LP, Butler R, Sodhi NS, Bradshaw CJA, Neidel JD, Consunji H, Mateo Vega J (2010) Improving the performance of the roundtable on sustainable palm oil for nature conservation. *Conserv Biol* 24(2):377–381
- Lewandowski I, Faaij APC (2006) Steps towards the development of a certification system for sustainable bio-energy trade. *Biomass Bioenergy* 30(2):83–104
- Liebig MA, Johnson HA, Hanson JD, Frank AB (2005) Soil carbon under switchgrass stands and cultivated cropland. *Biomass Bioenergy* 28(4):347–354
- Luyssaert S, Schulze ED, Börner A, Knohl A, Hessenmöller D, Law BE, Ciais P, Grace J (2008) Old-growth forests as global carbon sinks. *Nature* 455(7210):213–215
- Merino A, Fernandez-Lopez A, Solla-Gullon F, Miguel Edeso J (2004) Soil changes and tree growth in intensively managed *Pinus radiata* in northern Spain. *For Ecol Manage* 196(2/3):393–404
- Morton DC, DeFries RS, Shimabukuro YE, Anderson LO, Arai E, del Bon Espirito-Santo F, Freitas R, Morisette J (2006) Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proc Natl Acad Sci USA* 103(39):14637–14641
- Muller A (2009) Sustainable agriculture and the production of biomass for energy use. *Clim Change* 94(3):319–331
- New South Wales (2003) Native Vegetation Act 2003. Parliament of New South Wales, Sydney
- New South Wales (2007) Biofuels Act 2007. Parliament of New South Wales, Sydney
- O'Connell D, Braid A, Raison J, Handberg K, Cowie A, Rodriguez L, George BH (2009) Sustainable production of bioenergy: a review of global bioenergy sustainability frameworks and assessment system. Rural Industries Research and Development Corporation, Canberra
- Parliament E (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/E. *Off J Eur Union L* 140:47
- Paul KI, Polglase PJ, Nyakuengama JG, Khanna PK (2002) Change in soil carbon following afforestation. *For Ecol Manage* 168(1–3):241–257
- Perlack RD, Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. U.S. Department of Energy and U.S. Department of Agriculture, Oak Ridge
- Pimentel D (2006) Soil erosion: a food and environmental threat. *Environ Dev Sustain* 8(1):119–137
- Pimentel D (2009) Biofuel food disasters and cellulosic ethanol problems. *Bull Sci Technol Soc* 29(3):205–212
- Pimentel D, Patzek T (2007) Ethanol production: energy and economic issues related to U.S. and Brazilian sugarcane. *Nat Resour Res* 16(3):235–242
- Pimentel D, Marklein A, Toth M, Karpoff M, Paul G, McCormack R, Kyriazis J, Krueger T (2008) Biofuel impacts on world food supply: use of fossil fuel, land and water resources. *Energies* 1(2):41–78
- Pimentel D, Marklein A, Toth MA, Karpoff MN, Paul GS, McCormack R, Kyriazis J, Krueger T (2009) Food versus biofuels: environmental and economic costs. *Hum Ecol* 37(1):1–12
- Pingthina N, Leclerc MY, Beasley JP Jr, Zhang G, Senthong C (2010) Assessment of the soil CO₂ gradient method for soil CO₂ efflux measurements: comparison of six models in the calculation of the relative gas diffusion coefficient. *Tellus Ser B* 62(1):47–58

- Pinheiro EFM, Lima E, Ceddia MB, Urquiaga S, Alves BJR, Boddey RM (2010) Impact of pre-harvest burning versus trash conservation on soil carbon and nitrogen stocks on a sugarcane plantation in the Brazilian Atlantic forest region. *Plant Soil* 333(1/2):71–80
- Plevin RJ, O'Hare M, Jones AD, Torn MS, Gibbs HK (2010) Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated. *Environ Sci Technol* 44(21):8015–8021
- Pritchard SG (2011) Soil organisms and global climate change. *Plant Pathol* 60(1):82–99
- Raison RJ, Khanna PK (2011) Possible impacts of climate change on forest soil health. In: Singh B, Cowie AL, Chan KY (eds) *Soil health and climate change*. Springer, Heidelberg
- Raunikar R, Buongiorno J, Turner JA, Zhu SS (2010) Global outlook for wood and forests with the bioenergy demand implied by scenarios of the Intergovernmental Panel on Climate Change. *For Policy Econ* 12(1):48–56
- Reinhard J, Zah R (2009) Global environmental consequences of increased biodiesel consumption in Switzerland: consequential life cycle assessment. *J Cleaner Prod* 17(suppl 1):S46–S56
- Rengasamy P (2006) World salinization with emphasis on Australia. *J Exp Bot* 57(5):1017–1023
- Ribeiro SK, Kobayashi S, Beuthe M, Gasca J, Greene D, Lee DS, Muromachi Y, Newton PJ, Plotkin S, Sperling D, Wit R, Zhou PJ, Hata H, Sims R, Skjolsvik KO (2007) Transport and its infrastructure. In: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds) *Climate change 2007: mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, p 64
- Rice CW (2005) Carbon cycle in soils: dynamics and management. In: Daniel H (ed) *Encyclopedia of soils in the environment*. Elsevier, Oxford, pp 164–170
- Richard TL (2010) Challenges in scaling up biofuels infrastructure. *Science* 329(5993):793–796
- Richards AE, Forrester DI, Bauhus J, Scherer-Lorenzen M (2010) The influence of mixed tree plantations on the nutrition of individual species: a review. *Tree Physiol* 30(9):1192–1208
- Robertson FA, Thorburn PJ (2007) Management of sugarcane harvest residues: consequences for soil carbon and nitrogen. *Aust J Soil Res* 45(1):13–23
- Roundtable on Sustainable Biofuels (2009) RSB principles and criteria for sustainable biofuel production. Ecole Polytechnique Federale De Lausanne, Lausanne
- Sartori F, Lal R, Ebinger MH, Eaton JA (2007) Changes in soil carbon and nutrient pools along a chronosequence of poplar plantations in the Columbia Plateau, Oregon, USA. *Agric Ecosyst Environ* 122(3):325–339
- Schade C, Pimentel D (2010) Population crash: prospects for famine in the twenty-first century. *Environ Dev Sustain* 12(2):245–262
- Schlamadinger B, Marland G (1996) The role of forest and bioenergy strategies in the global carbon cycle. *Biomass Bioenergy* 10(5/6):275–300
- Schlamadinger B, Bird N, Johns T, Brown S, Canadell J, Ciccarese L, Dutschke M, Fiedler J, Fischlin A, Fearnside P, Forner C, Freibauer A, Frumhoff P, Hoehne N, Kirschbaum MUF, Labat A, Marland G, Michaelowa A, Montanarella L, Moutinho P, Murdiyarso D, Pena N, Pingoud K, Rakonczay Z, Rametsteiner E, Rock J (2007) A synopsis of land use, land-use change and forestry (LULUCF) under the Kyoto Protocol and Marrakech Accords. (Options for including agriculture and forestry activities in a post-2012 international climate agreement). *Environ Sci Policy* 10(4):271–282
- Searchinger T, Heimlich R, Houghton RA, Dong FX, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu TH (2008) Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* 319(5867):1238–1240
- Sims REH, Schock RN, Adegbululge A, Fenhann J, Konstantinaviciute I, Moomaw W, Nimir HB, Schlamadinger B, Torres-Martínez J, Turner C, Uchiyama Y, Vuori SJV, Wamukonya N, Zhang X (2007) *Energy supply*. Cambridge University Press, Cambridge
- Singh BP, Cowie A (2010) The mean turnover time of biochar in soil varies depending on biomass source and pyrolysis temperature. In: 19th world congress of soil science, soil solutions for a changing world, Brisbane, 1–6 Aug 2010. <http://www.iuss.org/19th%20WCSS/symposium/pdf/0326.pdf>. Accessed 1 December 2010

- Smolander A, Kitunen V, Tamminen P, Kukkola M (2010) Removal of logging residue in Norway spruce thinning stands: long-term changes in organic layer properties. *Soil Biol Biochem* 42(8):1222–1228
- Solomon BD (2010) Biofuels and sustainability. *Ann NY Acad Sci* 1185:119–134
- Solomon S, Qin D, Manning M, Alley RB, Berntsen T, Bindoff NL, Chen Z, Chidthaisong A, Gregory JM, Hegerl GC, Heimann M, Hewitson B, Hoskins BJ, Joos F, Jouzel J, Kattsov V, Lohmann U, Matsuno T, Molina M, Nicholls N, Overpeck J, Raga G, Ramaswamy V, Ren J, Rusticucci M, Somerville R, Stocker TF, Whetton P, Wood RA, Wratt D (2007) Technical summary. Cambridge
- Sparovek G, Berndes G, Egeskog A, de Freitas FLM, Gustafsson S, Hansson J (2007) Sugarcane ethanol production in Brazil: an expansion model sensitive to socioeconomic and environmental concerns. *Biofuels, Bioprod Biorefin* 1(4):270–282
- Sparovek G, Barretto A, Berndes G, Martins S, Maule R (2009) Environmental, land-use and economic implications of Brazilian sugarcane expansion 1996–2006. *Mitig Adapt Strateg Glob Change* 14(3):285–298
- Stehfest E, Bouwman L (2006) N₂O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. *Nutr Cycl Agroecosyst* 74(3):207–228
- Stern NH (2007) The economics of climate change: the Stern review. Cambridge University Press, Cambridge
- Tilman D, Cassman KG, Matson PA, Naylor R, Polasky S (2002) Agricultural sustainability and intensive production practices. *Nature* 418(6898):671–677
- Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. *Science* 314(5805):1598–1600
- Tilman D, Socolow R, Foley JA, Hill J, Larson E, Lynd L, Pacala S, Reilly J, Searchinger T, Somerville C, Williams R (2009) Beneficial biofuels – the food, energy, and environment trilemma. *Science* 325(5938):270–271
- Turner J, Lambert M (2000) Change in organic carbon in forest plantation soils in eastern Australia. *For Ecol Manage* 133(3):231–247
- Tyner WE, Taheripour F, Zhuang Q, Birur D, Baldos U (2010) Land use changes and consequent CO₂ emissions due to US corn ethanol production: a comprehensive analysis. Purdue University, West Lafayette
- United Nations (2008) Partnerships for sustainable development. United Nations, Rome
- Uslu A, Faaij APC, Bergman PCA (2008) Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. *Energy* 33(8):1206–1223
- van Dam J, Junginger M, Faaij A, Jürgens I, Best G, Fritsche U (2008) Overview of recent developments in sustainable biomass certification. *Biomass Bioenergy* 32(8):749–780
- van Dam J, Junginger M, Faaij APC (2010) From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. *Renewable Sustainable Energy Rev* 14(9):2445–2472
- Vargas Gil S, Becker A, Oddino C, Zuza M, Marinelli A, March G (2009) Field trial assessment of biological, chemical, and physical responses of soil to tillage intensity, fertilization, and grazing. *Environ Manage* 44(2):378–386
- Vertessy RA, Zhang L, Dawes W (2003) Plantations, river flows and river salinity. *Aust Forest* 66:55–61
- Vis MW, Vos J, van den Berg D (2008) Sustainability criteria and certification systems for biomass production. Biomass Technology Group, Enschede
- Vivid Economics (2010) The implicit price of carbon in the electricity sector of six major economies. The Climate Institute, Sydney
- Walmsley JD, Godbold DL (2010) Stump harvesting for bioenergy – a review of the environmental Impacts. *Forestry* 83(1):17–38

- Wang H, Brown SL, Magesan GN, Slade AH, Quintern M, Clinton PW, Payn TW (2008) Technological options for the management of biosolids. *Environ Sci Pollut Res* 15(4):308–317
- Warnock D, Lehmann J, Kuyper T, Rillig M (2007) Mycorrhizal responses to biochar in soil – concepts and mechanisms. *Plant Soil* 300(1):9–20
- Wicke B, Sikkema R, Dornburg V, Faaij A (2011) Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. *Land Use Policy* 28(1):193–206
- Wijffels RH, Barbosa MJ (2010) An outlook on microalgal biofuels. *Science* 329(5993):796–799
- Wit MD, Faaij A (2010) European biomass resource potential and costs. *Biomass Bioenergy* 34(2):188–202
- Wood S, Cowie AL (2004) A review of greenhouse gas emission factors for fertiliser production. Task 38. IEA Bioenergy, Sydney
- Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. *Nat Commun* 1(5):56